

The United States Clean Coal Research, Development and Demonstration Program

**Presented by
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Introduction

The future of coal in the United States – and quite likely, throughout much of the world – will be a future determined largely by technological innovation. Coal reserves are plentiful – in the United States, recoverable coal reserves amount to 297 billion tons, enough to sustain the nation's current rate of consumption for more than 250 years. Coal is the most affordable fuel for large-scale power generation – in the United States, the 12 lowest cost-of-electricity power plants and 82 of the 100 lowest cost power plants are fueled by coal.

But of all the fossil fuels, coal faces perhaps the most serious challenges. In the United States, tighter air quality regulations for nitrogen oxides, fine particulates and possibly mercury may be applied to fossil fuel power generation. Concerns over global climate change have the possibility of imposing serious restrictions on the future use of coal. At the same time, the restructuring of the U.S. electric power industry is creating intense pressures on power producers to reduce costs and to avoid large, higher-risk capital investments.

None of the power and fuel subsystems currently being developed in the U.S. Department of Energy's (DOE) coal research, development and demonstration program can

individually meet the twin challenges of environmental compliance and economic competitiveness in the 21st century, especially given expectations for continuing low energy prices.

Therefore, DOE is reorienting its ongoing technology programs in both coal-based electricity and fuels conversion to converge on a common goal – a new multi-fuel, multi-product energy complex.

Such a facility, we believe, will be capable of responding to future environmental pressures, including the challenge of reducing future greenhouse gas concentrations. We also see the prospects for such a facility achieving economic parity with power facilities fueled by natural gas and other competing fuels.

At the core of such a complex would be power generation; but rather than being limited to a single feedstock producing a single product, such a complex would be capable of processing coal, natural gas, biomass or a combination into a range of products. In its ultimate configuration, electric power could be only one – albeit the most significant – of a slate of products that would also include liquid fuels and chemicals along with process heat. The exact mix of feedstocks and products would be dictated by site-specific market considerations.

Our goal is that such a future energy facility would have virtually no environmental impact. Conventional pollutants would be captured and either disposed of or converted to marketable co-products. There would be no solid or liquid discharges. Creation of carbon dioxide and other greenhouse gases would be reduced by ultra-high efficiency technologies, then carbon emissions would be captured at the plant or offset by carbon removal processes applied elsewhere. The captured carbon would be sequestered or potentially recycled into useful products.

We have called this new concept the “Vision 21 PowerPlex” because, to us, it represents the most effective way to keep coal in the world’s energy future in the 21st century.

The Vision 21 Program

The “Vision 21 PowerPlex” program is a long-range, cost-shared, industry-driven

research and development effort designed to produce public benefits beginning within a decade and extending well into the next century.

The program will integrate emerging concepts for high-efficiency power production and pollution controls into a new class of fuel-flexible electricity power generation facilities. It will also offer a “market-entry” strategy for new concepts to produce high value fuels and chemicals from coal and other feedstocks. Discrete technology modules will offer future plant designers maximum flexibility in their choice of products, feedstocks and environmental controls. Planners will be able to select modules according to feedstock supply and product demands of an individual region. The Vision 21 program will be comprised of:

- *Enabling technologies*, such as advanced, low-cost hydrogen and oxygen separation and advanced gas cleaning,

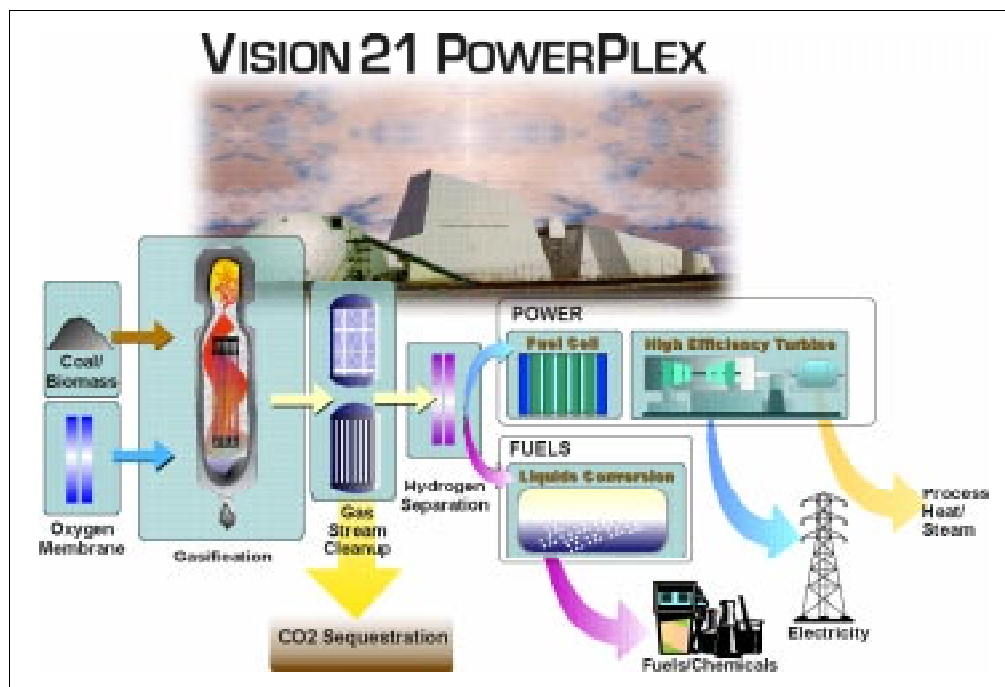


Figure 1 - A gasification-based configuration for the Vision 21 PowerPlex

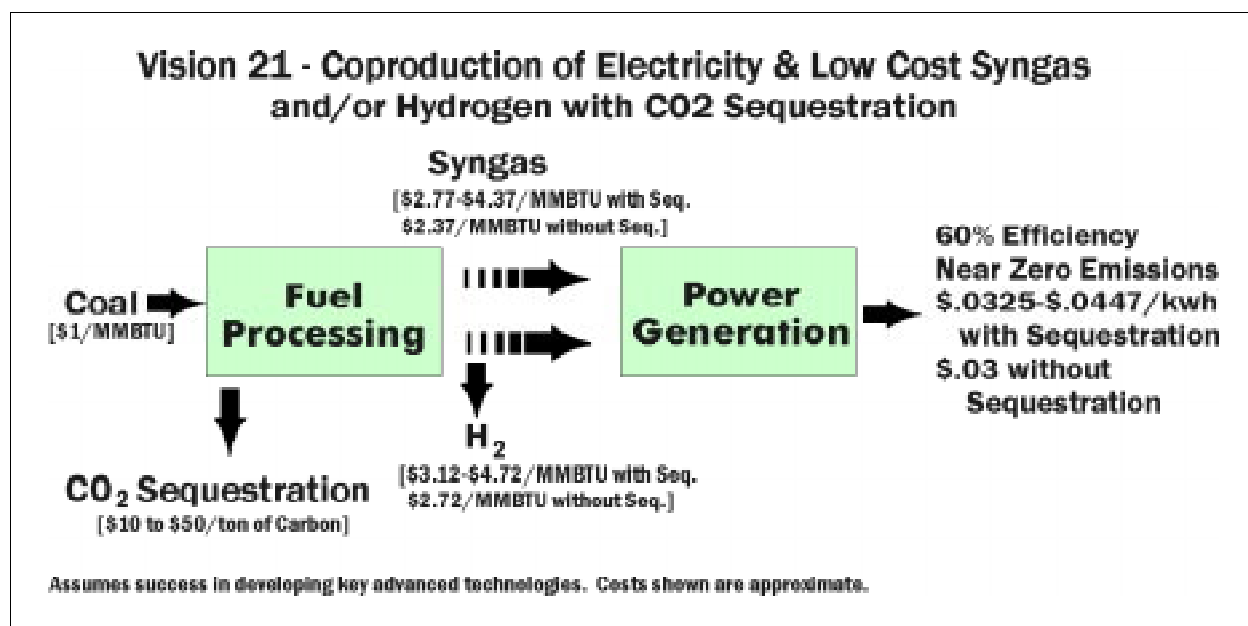


Figure 2 - The Vision 21 PowerPlex will be capable of generating electricity from coal at costs that are competitive with other fuel sources.

- *Supporting technologies*, such as higher-strength, more durable materials, improved catalysts, environmental control technologies, sensors and controls, and virtual demonstrations,
- *Systems integration* that will link power generation with liquids conversion and process heat production for optimal performance and system efficiencies , and
- *Plant designs* that would serve as the basis for a new fleet of commercial-scale Vision 21 plants.

Vision 21 provides a technology roadmap for progressively cleaner and more efficient energy production. As the program evolves in coming years, this roadmap will guide development efforts in:

Oxygen-separation technologies. To reduce capital costs and increase the efficiency of the Vision 21 concept, as well as other

gasification-based energy systems, new low-cost air separation technologies will likely be necessary to produce high-purity streams of oxygen.

In addition, to meet anticipated constraints on the release of CO₂, either novel technologies will have to be developed for separating CO₂ from flue gas or new process configurations must be designed to concentrate CO₂ directly. Concepts to accomplish the latter have been proposed, but require the use of pure oxygen rather than air, a requirement which adds to the capital and operating costs of conventional powerplants.

DOE-sponsored R&D has identified a novel class of dense ceramic materials called ion transport membranes (ITM). These membranes (molecular sieves) use mixed-conducting ionic ceramics that conduct both oxygen ions and electrons through the membrane wall. A recent study quantified the impact of advanced-membrane technology on

the integrated gasification combined cycle technology for electric power generation. The initial results showed a 31 percent decrease in the cost of oxygen, a decrease in a total capital investment of \$114/kW, a 2.9 percent increase in thermal efficiency, a 6.5 percent decrease in the cost of electricity, compared to current baselines. In addition, this technology has crosscutting potential in areas such as the steel, glass and pulp and paper industries.

Although these benefits are substantial, formidable challenges block development of oxygen separation technology. These challenges will be addressed in a three-phase program spanning about 7 years. The first phase addresses high-risk materials development, membrane fabrication, membrane performance, and engineering issues related to process integration. Subsequent phases will focus on scale-up of the membranes and fabrication techniques, evaluation of full-scale modules, process integration, and validation of process engineering and economic models.

Hydrogen-separation technologies. The power generation portion of the Vision 21 concept could include advanced fuel cell technology, fueled by hydrogen produced by gasifying coal or biomass. Future multi-product Vision 21 plants could also produce hydrogen as a fuel for transportation purposes (perhaps serving as transition to a hydrogen-based economy).

No commercial technologies exist today, however, that can separate hydrogen from gasification products at high temperatures and pressures.

Researchers in DOE's program are investigating novel hydrogen separation

technologies that are capable of operating at elevated pressures and temperatures while tolerating the presence of chemical and particulate contaminants in the gas stream.

Ceramic membranes could accomplish the separation economically. DOE's initial approach will concentrate on fabricating ion transport membranes that have sufficiently small pores and permit only the passage of hydrogen molecules through the membrane wall at high temperatures and pressures.

A second approach is to develop dense ceramic membranes that conduct hydrogen as protons (proton transfer membrane) through the membrane wall in much the same way as an ion transfer membrane.

Both approaches will focus R&D efforts on the water-gas shift reaction to supply additional hydrogen and other possible products.

High-temperature heat exchangers.

High-temperature heat exchangers, which transfer heat from hot-combustion products to the working fluid, are key components in systems using steam turbines or indirectly-fired cycles. Today, maximum temperatures in steam turbine plants are limited to about 1,050° F to 1,100° F. For more efficient ultra-supercritical plants, high-efficiency heat exchangers are needed to superheat and reheat steam to temperatures of 1,100° F to 1,300° F or higher. These heat exchangers require advanced alloys that have both high-temperature strength and corrosion resistance. New alloys are being developed in DOE's Advanced Materials Program, but long-term testing will be required before they can be certified for use in large commercial powerplants. When these improved alloys are

available, conventional powerplants with efficiencies of 45 to 50 percent will become possible and Vision 21 plants with 60 percent efficiency will be achievable.

Fuel-flexible gasification. Since gasification-based systems are the principal advanced power-generating technology capable of coproducing electricity and other valuable fuels and chemicals, advanced gasification technology capable of processing a variety of feedstocks is a key core system in the Vision 21 PowerPlex concept.

Investigations will focus on: (1) defining the availability and cost of alternative feedstocks and identifying obstacles to achieving technical success, (2) evaluating alternative feedstocks in existing gasification facilities such as Clean Coal Technology projects, and in developmental units such as the transport reactor at the Wilsonville Power Systems Development Facility, and (3) developing novel gasification concepts that can lower costs and improve efficiency, feedstock flexibility, and modularity. Such technologies may include catalytic gasification to improve the hydrogen content of the product, the use of novel ceramic membrane approaches (such as the ion transport membrane), the use of CO₂ instead of steam as the diluent for oxygen feed to the gasifier in systems that capture CO₂ for sequestration.

Advanced hot-gas cleanup. Key to achieving Vision 21 goals of high efficiencies, near-zero emissions, and low cost is the cleaning and conditioning of gasification and combustion-product gases. Gases must be cleaned of particulate matter, all sulfur- and nitrogen-containing compounds, and all traces of other hazardous compounds at temperatures and pressures close to gasifier/combustor

operating conditions and to those of downstream operations. Research activities will focus on:

- Developing high-efficiency, high-temperature particulate filters that operate in either an oxidizing or reducing environment. Performance will be demonstrated in long-term integrated operations at existing DOE facilities.
- Investigating new classes of catalysts or advanced sorbents capable of decomposing and/or removing chemical contaminants at high temperatures. These catalysts and sorbents may be used in conjunction with high-temperature ceramic membrane technologies to decompose a contaminant, while simultaneously separating hydrogen from the gas stream for use in high-efficiency fuel cells.

Advanced combustion systems. The indirectly fired combined cycle is promising because of its potential for high thermal efficiency without hot-gas cleanup and its capability to handle a wide variety of fuels, including wastes. This makes it an attractive candidate for a key technology module for Vision 21, as well as for new, high-efficiency powerplants or for repowering existing plants.

An indirectly fired combined cycle is a system in which a major portion of the heat input to the gas turbine is added by indirect heating. The main benefit is that coal can be used in high-efficiency gas turbines without the need for hot-gas filtration devices.

The key to developing an indirectly fired cycle is learning how to transfer heat from coal combustion to the turbine air in a high

temperature advanced furnace (HITAF). This requires both innovative engineering and advanced materials. To realize high system efficiency, the HITAF must operate at higher temperatures than conventional coal-fired steam boilers.

Two industrial teams have been developing different versions of the high performance power system concept. When fully developed, both versions are to be capable of achieving the very high efficiencies needed for Vision 21. Less advanced configurations, available now, can be used to repower existing coal-fired plants and thus increase both their power output and efficiency.

In some Vision 21 configurations, pressurized fluidized bed combustion may be integrated into the power generation train. R&D efforts underway at DOE are focusing on reducing capital and production costs. This work includes simplification of fluidized bed combustion systems and components, incorporation of alternative feed and withdrawal systems and the development of advanced subsystems and steam cycles.

Developing and demonstrating a topping combustor with suitable fuel flexibility, flame stability, and NO_x-emissions characteristics is critical to commercializing second-generation pressurized fluidized bed combustion systems. Tests of a multi-annular swirl burner (MASB) have demonstrated good flame stability and NO_x performance. Follow-on systems testing of the MASB will be performed in the Wilsonville Power Systems Development Facility by the end of 1998, and integration of the MASB into advanced turbine system designs will occur after the turn of the century.

Results from system studies will guide future R&D. In 1998, optimum turbine-compressor configuration and operation of first-generation pressurized fluidized bed systems are being studied. In future years, optimum configurations of second-generation pressurized fluidized bed systems for Vision 21 plants integrated with fuel cells and CO₂ sequestration options will be developed. Gas turbine studies will be performed on gas compositions and heat capacities specific to pressurized fluidized bed combustion, which can lead to higher allowable turbine blade temperatures.

Fuel cell/gas turbine hybrids. Two DOE-sponsored workshops on high-efficiency, fuel cell hybrid systems led to a competition that resulted in three research projects to develop conceptual systems for future fuel cell/gas turbine hybrid systems.

The hybrid system configures the high-temperature, advanced fuel cells with a low-pressure ratio gas turbine, air compressor, combustor, and metallic heat exchanger. Electrical conversion efficiencies of 72 to 74 percent (LHV) are calculated for this system. The typical system size is 3 to 10 MW. Also, preliminary studies have shown that efficiencies of more than 85 percent are possible.

DOE is continuing to focus its power generation fuel cell R&D on molten carbon and solid oxide technology, both of which are applicable to the fuel cell/gas turbine hybrid concept. Program goals are to lower power plant costs for either technology to under \$1,500/kW by 2003, sufficient to begin attracting firm commercial orders for natural gas-fueled systems. By 2010 (assuming commercialization of hot gas cleanup by

2005), the goal is to bring coal-fueled fuel cell power plants to a state of market readiness.

Fuel-flexible turbines. DOE's Advanced Turbine Systems program is close to completing development of a prototype utility gas turbine with remarkable improvements in efficiency and environmental performance. During the next two years, testing will be completed for full-scale components and subsystems and the manufacturing capability will be in place for the first test engines. Site preparation will begin for the critical full-speed tests scheduled for the final phase of the initial R&D program. By 2002, commercial readiness should be achieved for a natural gas-fired turbine capable of operating in temperature regimes of approximately 2,600° F, with 60% efficiencies (LHV), single digit (ppm) NO_x emissions, and projected costs of electricity 10 percent lower than today's gas-fired combined cycle systems.

To achieve Vision 21 goals, however, advanced turbine technology will have to be applied to coal-based systems, either adapted to use fuel gas derived from gasifiers or integrated with pressurized fluidized bed combustor. Advanced-cycle configurations with increased pressure ratios, more durable alloys and ceramic materials, and advanced combustion technology, such as lean pre-mix and catalytic systems, likely will be necessary.

By 1999, DOE will complete systems studies and collect stakeholder inputs to define enabling gas turbine technologies for coal-based Vision 21 power modules. Program milestones, resources, and goals will be defined. Systems studies will evaluate the potential for advanced cycles, materials, combustion systems, and cooling concepts to achieve Vision 21 goals. By 2001,

opportunities to transfer advanced turbine technology to coal-fueled systems will be identified, and DOE anticipates conducting full-scale tests of advanced turbine technology in combination with integrated gasification combined cycle, pressurized fluidized bed and high performance power systems by 2003, with demonstrations completed by 2005.

Enhancements to the technology will permit, by 2008, full-scale testing of Vision 21 concepts to be completed. Demonstrations of advanced gas turbine-based power modules in Vision 21 plants could be held by 2010.

Coproduction of Power and Fuels.

Coproduction integrates two concepts now carried out commercially in separate facilities: gasification-based power production and indirect liquefaction. Preliminary studies show that integrating these technologies into a single facility can offer significant economic and environmental benefits when compared to stand-alone plants. A Vision 21 complex that produces both electricity and fuels/chemicals may also be attractive because of its CO₂ management.

The innovation involved in a Vision 21 coproduction facility would be the integration of a highly efficient power cycle with Fischer-Tropsch synthesis and capture and sequestration of substantially all of the CO₂ produced.

In such a facility, net carbon emissions associated with fuel use would depend on the composition of the fuel. If the principal fuel products are diesel/gasoline, the net carbon emissions would be less than or equal to those that would result if the fuels had been produced by petroleum refining. If hydrogen were the principal product, obtained by

employing the water-gas shift reaction with synthesis gas, nominally zero net carbon emissions would result if coal were used. If biomass were fed to the coproduction facility, there could actually be a net decrease in atmospheric CO₂ from the cycle of biomass growth, collection, conversion to power and fuel, and fuel consumption. Complete capture and sequestration of CO₂ produced at the Vision 21 facility is assumed.

DOE's current research program is focused on developing clean fuels that: 1) are environmentally superior to those derived from conventional petroleum-based fuels; 2) can satisfy the liquid fuel requirements of our nation's transportation infrastructure; and 3) will help the engine and vehicle manufacturers achieve higher performance with significantly lower emissions in both conventional and advanced systems. R&D partnerships between DOE and industry, academia, national laboratories and other government organizations are pursuing cost-shared research and engineering studies with a goal of a privately-funded, first-of-a-kind commercial facility by 2007 that coproduces multiple products – some combination of power, fuels, chemicals and process heat.

To achieve this goal, R&D is continuing in both direct and indirect liquefaction. Research is showing the prospects for reducing the cost of producing direct liquids to around \$21 per barrel by coprocessing coal with low- or negative-value wastes. These liquids can be upgraded, at lower cost than crude oil, using conventional petroleum refining technologies to produce high-octane gasoline, jet fuels, and valuable chemicals. The fuels have much lower levels of pollutant-producing sulfur and nitrogen than those of typical petroleum crude.

R&D will pursue process improvements in the direct hydrogenation of coal – alone, and in combination with petroleum resid and, possibly, waste material – including the development of more efficient reactors, more active and robust slurry catalysts, and methods that produce hydrogen more economically and reduce its consumption during liquefaction.

Research will also be carried out to reduce the production of greenhouse gases from the coal liquefaction process. Large amounts of CO₂ are generated during the production of the necessary hydrogen. To reduce CO₂ emissions, DOE will examine ways to integrate hydrogen production from non-carbon sources into the liquefaction process. Further greenhouse gas reductions, if needed, could also be achieved using carbon sequestration.

In the indirect liquefaction of coal, novel, three-phase slurry reactor technology is being developed to produce premium fuels and high-value chemicals. Continued iron-catalyst development will be aimed at increasing catalyst versatility to coproduce high-value, linear chain olefins along with liquid fuels. Development of an improved dimethyl ether catalyst has progressed well at bench scale and is ready for proof-of-concept demonstrations. New research will be initiated to couple the dimethyl ether to form a liquid oxygenate mixture that has a cetane number exceeding 100; this would be an excellent diesel fuel blending component.

We plan to solicit industry proposals in 1998 to cost-share feasibility studies, conduct R&D, and prepare preliminary designs for a first-of-a-kind commercial, multi-product “energyplex” plant. This effort will enable development teams to refine their strategies,

reduce technical risks, and define economic and environmental requirements for future Vision 21 concepts.

Supporting Technologies. Integral to the Vision 21 concept is directed research on materials, components, controls, sensors, computer modeling, and other supporting technologies that cut across existing product lines. Much of this work is jointly defined and sponsored with a diverse group of industrial partners.

Materials and components. Materials and components research directly addresses the needs of such Vision 21 enabling technologies as hydrogen and oxygen separation and high-temperature heat exchangers. Of particular importance will be the Combustion and Environmental Research Facility at DOE's Federal Energy Technology Center that can evaluate materials like ceramic boiler tube and material coupons under a variety of simulated harsh boiler environments and using different fuels.

Virtual Demonstrations. As R&D budgets tighten and computer power and capabilities expand, the use of models and simulations will become increasingly important as a cost-effective method for designing, developing, testing, evaluating and simulating new energy technologies, including the Vision 21 PowerPlex concept.

Virtual demonstrations are already being used in other industries, e.g., aircraft design and manufacturing, as a cost-effective tool to reduce scale-up, construction, and operational risks. The results of such modeling will be invaluable for identifying opportunities and steering supporting research. Research results

can then be used to confirm the performance of modeling segments.

The Vision 21 concept provides maximum flexibility with respect to products, feedstocks, and environmental controls. Individual modules will be demonstrated first, and then modules will be linked together to constitute Vision 21 plants. With relatively few modules, the number of design variations is already large, and the most cost-effective -- and perhaps the only -- way to demonstrate all configurations/designs will be by using "virtual demonstrations."

In addition, the virtual demonstration may be used in a predictive fashion and may prioritize combinations and permutations of modules for a Vision 21 plant for a specific site, based on feedstock availability, population density, environmental attainments and markets for coproducts.

Advanced controls and sensor systems. With the advent of advanced power-generation and fuel conversion technologies such as those proposed for Vision 21, a new generation of advanced controls and sensors must be developed.

The new controls and sensors will be compact, modular, inexpensive and easy to maintain. They will maximize the operational efficiency of advanced fossil fueled processes while reducing emissions, as mandated by the latest federal regulations for NO_x, SO₂, mercury, PM_{2.5}, and greenhouse gases. This technological advance will maintain the economic and environmental advantages of fossil plants over alternative power generation sources.

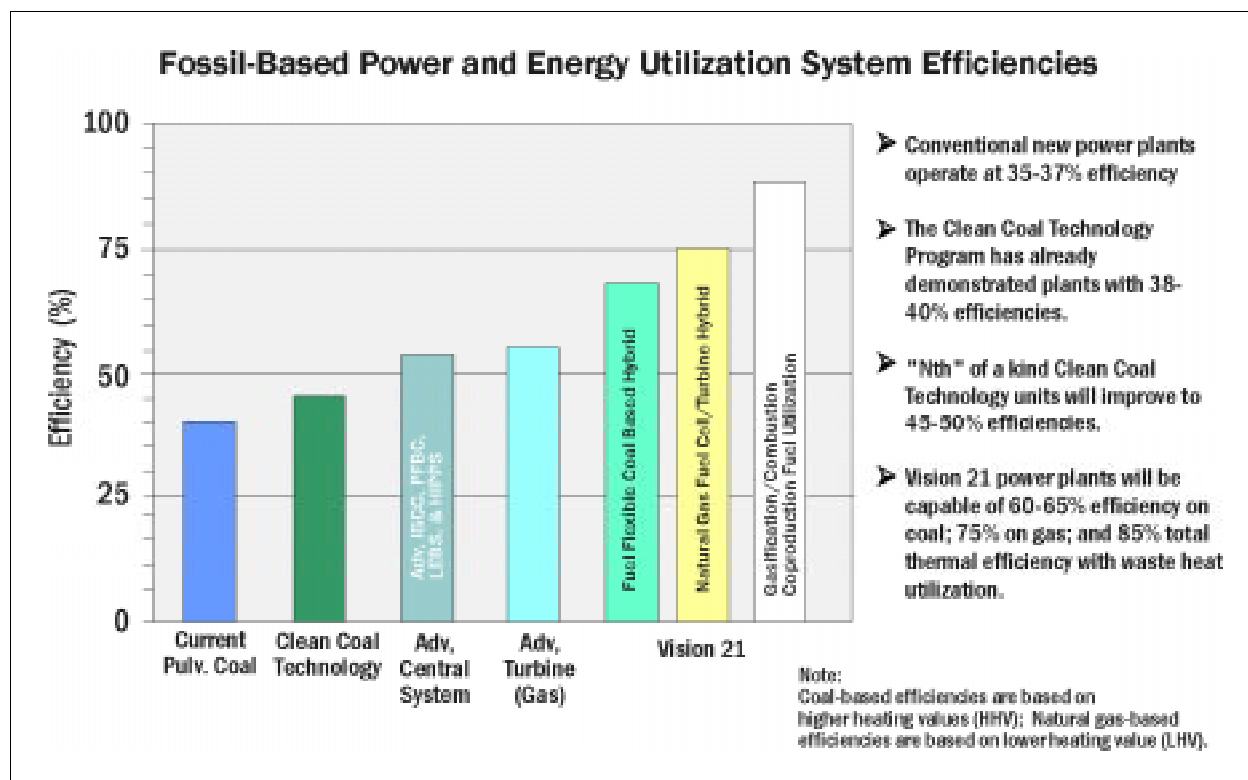


Figure 3 - The Vision 21 concept can push coal and natural gas system efficiencies to maximum levels.

Modularization. Rather than today's common practice of designing most large industrial and utility fossil fuel plants on a site-by-site basis, Vision 21 plants would be built from modules, standardized to the greatest extent possible. Modular design and construction will maximize shop fabrication, minimize expensive field construction and maintain flexibility in the design and deployment of Vision 21 plants. The use of standardized modules could also expedite regulatory permitting, resulting in significant time and cost savings. Environmental controls would, in general, be integrated within individual modules but may be stand-alone modules if they prove to be advantageous from an economic or operational standpoint.

Systems/Market Analyses. Systems analysis is a critical part of the Vision 21 Program and

serves to guide all activities. The key role of systems analysis is to develop Vision 21 system configurations that meet the program objectives and also to define the performance targets for individual subsystems and supporting technology needs. Systems analysis activities will include development of computer simulation software, definition of Vision 21 system configurations, system evaluations, economic analysis, and virtual demonstrations. Modeling can be used to identify alternative process configurations and results comparisons and thus identify the most promising approaches for achieving the cost and performance targets for Vision 21. Modeling also identifies RD&D areas capable of yielding the greatest return on government investment and increasing RD&D cost-effectiveness.

Carbon Sequestration

DOE sequestration research program envisions the development of technologies suited to point-source greenhouse gas capture, a key element of the Vision 21 concept. In addition, the program is examining techniques for enhancing natural carbon sinks to create greenhouse gas reduction credits. Our intent is to develop a set of sequestration options that could offset all new growth in greenhouse gas emissions after 2010.

Our R&D objectives are to verify the environmental acceptability, technical feasibility, and cost-effectiveness of a sufficient sequestration capacity for the required wide-scale implementation starting in 2015. During the 2005 to 2015 time period, a suite of cost effective options with increasingly large carbon sequestration capacity will be made available. The program will also seek to develop even lower cost options by the 2020 time frame. The long-term cost goal is in the range of \$10/ton of carbon sequestered.

The strategy for achieving this is to build upon ongoing scientific, technical, and environmental research using domestic and international cost-shared collaborations with industry, universities, and other governments (e.g., the International Energy Agency Greenhouse Gas R&D Programme, the Climate Technology Initiative of the Framework Convention on Climate Change [Working Group 3] and other agreements).

Elements of this program include:

Enhanced Natural Sinks/Offsets. The annual exchange of CO₂ between the atmosphere and the combined ocean and

terrestrial biosphere is extremely large compared to total annual anthropogenic emissions. This suggests that small increases in the absorption of CO₂ as an enhancement of the global carbon cycle could have a significant effect on net greenhouse gas atmospheric concentrations.

Dissolved CO₂ in the oceans is removed by the growth of phytoplankton. When carbon is thus removed, it is ultimately replaced by CO₂ drawn from the atmosphere. Numerous concepts have been proposed for enhancing oceanic uptake of atmospheric CO₂.

For direct ocean storage, the most critical R&D questions include the diffusivity of CO₂ in the ocean as a function of temperature, depth, and concentration, as well as the stability of CO₂ clathrates and hydrates at various temperatures and ocean depths. In addition, the biological impacts of oceanic injection need to be studied.

In FY 1999, the emphasis in ocean storage research will be on continuing the collaborative international research project initiated in FY 1998 with Japan and Norway; on broadening the international collaborative participation in research in this pathway; and on supporting scientific, environmental, and technology research activities.

A recent study by the IEA Greenhouse Gas R&D Programme has confirmed that there are large, cost-effective, potential sequestration opportunities. To achieve potential benefits, however, barriers to the application of advanced forest-management technologies, for example, must be overcome.

Carbon sequestration in soils is also a key part of the carbon cycle. The fundamental concept

is the level of soil organic matter. In this area, research is needed to develop practical and economic technology approaches to increasing organic matter in the soil and to inexpensively monitor changes in it.

In FY 1999, the emphasis will be on innovative concepts resulting from the FY 1998 “novel concepts” solicitation (that resulted in 12 DOE-sponsored projects); integration of sink enhancement with fossil fuel production and use; and other elements of the sequestration and Vision 21 programs. Collaboration with other elements of the Department of Energy (e.g., the Carbon Management Sciences Programs of the Office of Energy Research) and others, as well as continuation of international collaborative activities in this area through the IEA Greenhouse Gas R&D Programme, are also envisioned. A key objective of all these activities will be to find innovative ways to integrate sink enhancement with the efficient production, conversion, and use of fossil fuels.

Capture and Separation Technology. Sequestration from large point sources also requires cost-effective capture of carbon, whether it is CO₂, CO, or C, and its separation from other constituents not destined for sequestration. Some capture and separation technology is available but is costly and inefficient. In many cases, the costs of capture and separation far exceed the costs of transportation and sequestration.

Fuels production and conversion processes can be modified to enhance carbon capture, but to do so in a cost effective manner will require innovative technologies.

In FY 1999, the emphasis will include projects to address improvements in the technical and

economic performance of known technologies and continuation of collaborative activities through the IEA Greenhouse Gas R&D Programme.

Geologic/Ocean Storage. Another set of promising concepts for reducing CO₂ concentrations is storage in geologic formations. It is believed that CO₂ could be cost effectively sequestered in these formations.

Options for geologic storage of CO₂ include sequestration in depleted or depleting oil or gas wells, coal seams, or deep underground saline formations. Statoil of Norway is currently sequestering CO₂ in a deep saline reservoir under the North Sea, the first practical project of its kind. Critical research questions center on understanding the effects of CO₂ on the chemical and physical properties of storage sites, environmental impacts, total potential storage capacity, and the economics of various candidate sites.

In FY 1999, the emphasis on geologic storage will build upon the international research collaboration with the IEA Greenhouse Gas R&D Programme, including the recently initiated partnership in deep, unmineable coal seams, which is being implemented by a group of U.S. and Canadian firms, various Canadian research agencies, and DOE’s Office of Fossil Energy. Projects selected under the FY 1998 solicitation will be pursued as will exploratory research on depleting and depleted oil and gas reservoirs.

Chemical and Biological Pathways for Carbon Sequestration. Advanced chemical and biological sequestration is aimed at permanent, stable sequestration and at recycling carbon to create new fuels, chemical

feedstocks, and other products. Reducing emissions is accomplished by converting CO₂, CO, or C into an environmentally benign, economically useful product. The major advantage of these technologies is that they produce economically valuable products for the global economy while meeting a global environmental goal. All concepts for these technologies, listed below, are at an early research stage:

- Conversion of CO to new, carbon-based products
- Chemical sequestration as a carbonate mineral
- Direct conversion of CO₂ into methanol/benign products
- Decarbonization of fossil fuels/capture of excess carbon
- Microalgae sequestration
- Biomimetic fixation of carbon

Better understanding of the basic processes and new chemistry and bioprocessing approaches is needed before practical, achievable technology performance or cost levels can be estimated. FY 1999 research in this area will emphasize projects selected under the FY 1998 innovative novel-concepts solicitation and other solicitations; other opportunities to be identified through the ongoing research-needs roadmapping; collaboration with DOE's Office of Energy Research; and continued international collaborations through the IEA Greenhouse Gas R&D Programme.

Other Coal R&D Activities

While the Vision 21 and carbon sequestration R&D programs represent new areas of emphasis for DOE's coal research and development program, other important coal-

related technology efforts are also being pursued. These include programs to develop:

- *Environmental compliance and performance improvements for existing plants*
- *A new low-emission pulverized coal boiler system, and*
- *Cleaner, high-value solid fuels and feedstocks.*

Environmental compliance and performance improvements for existing plants. A critical need in the United States is for more cost-effective technologies to improve the efficiency, economics and environmental performance of the current 300-gigawatt fleet of aging U.S. coal-fired power plants.

Environmental improvements. The U.S. electric utility industry has made major strides in reducing emissions of SO₂, NO_x, and particulates since passage of the 1970 Clean Air Act and its subsequent amendments. Emissions of SO₂ from the 445 Phase I units have been reduced from 1980 levels of 10.9 million to 5.3 million tons. NO_x emission rates from utility boilers are 40 percent below 1990 levels, from an average of 0.65 lb/mm Btu to an average of 0.39 lb/mm Btu. Particulate emissions from the utility sector have decreased by nearly a third since 1988.

Yet, further improvements will be required to meet even more stringent regulations in the future.

Within the coming decade, DOE's R&D program is developing (1) post-combustion NO_x control technology, such as Selective Non-Catalytic Reduction (SNCR) coupled with Selective Catalytic Reduction (SCR),

capable of meeting NO_x emission standards for ozone mitigation that cost 25 to 50 percent less than standalone SCR, (2) post-combustion control technology that will be capable of increasing the overall collection efficiency of primary fine particulates to 99.99 percent, especially for particles in the 0.1 to 1.0 micron range, (3) a suite of mercury control technologies that can remove all forms of mercury from coal combustion flue gas.

Repowering. Repowering existing coal-fired steam-generating units can boost generating capacity, improve efficiency, and reduce CO₂, SO₂, NO_x, and particulate emissions – all at competitive costs. The additional capacity and the typically low production cost of a highly efficient, coal-fired, advanced power system translates into high-capacity factors and a steady revenue stream.

Repowering is made even more attractive because of a suite of flexible power systems, allowing an optimum repowering strategy to be developed for site-specific situations. One common option is hot windbox repowering. In this approach, hot exhaust from a gas turbine is directed into the windbox of an existing boiler, eliminating the need for forced-draft fans, increasing generating capacity up to 25 percent, and increasing efficiency by as much as 15 percent. Generally suitable for newer units larger than 300 MW, hot windbox repowering can be a low-cost option.

Feedwater heating is another low-cost repowering option. In this approach, heat from the exhaust of a gas turbine is used to heat feedwater for the existing boiler. The benefits are a capacity increase of up to 30 percent and an efficiency improvement of 5 to 10 percent.

DOE's Federal Energy Technology Center has studied the technical and economic feasibility of repowering typical existing fossil electric powerplants with a range of advanced power system technologies developed through DOE sponsorship. By repowering with clean, efficient power systems, such as pressurized fluidized-bed combustor, integrated gasification combined cycle, and high performance power system, the net power capacity increases from 20 to 175 percent and the net relative plant efficiency can increase by more than 30 percent, depending on which repowering technology is used.

Artificial intelligence. Modern control systems have significantly improved the operating performance – in terms of both cost and environmental performance – of coal-fired power plants in retrofit and new installations. The complexity of the optimization problem, however, has limited the benefits achieved by conventional systems.

For example, optimizing a boiler's burners to reduce NO_x emissions often results in higher levels of unburned carbon in the flyash, which can make the ash unsaleable to the cement industry thus increasing a plant's operating costs (because the ash would then have to be disposed of in a landfill). This problem is exacerbated by the low-NO_x burners that many plants have been required to install to meet the new lower NO_x regulations.

Embedding artificial intelligence (AI) in a power plant's digital control system has emerged as the best approach for balancing the complexity of different operating parameters. Several commercial software systems have recently been developed.

One of these AI systems – the Generic NO_x Control Intelligent System (GNOCISJ) – was developed under an extension to a DOE Clean Coal Technology project conducted by Southern Company Services, Inc. GNOCISJ was demonstrated at Georgia Power Company's Plant Hammond Unit 4 (a 550-MW, opposed wall-fired unit). At full load, it has achieved an efficiency improvement of 0.5 percentage points, a 3-percent point reduction in the unburned carbon content of the unit's fly ash, and a reduction of 15 percent in NO_x emissions. To date, coal-fired plants totaling approximately 8500 MW (7000 MW in the U.S. and 1500 MW in the U.K.) have installed or are installing GNOCISJ.

Potentially, all fossil fuel-fired plants could be retrofitted with AI systems, which will save the electric utility industry many millions of dollars in operating and environmental control costs.

A new low-emission pulverized coal boiler system. DOE's cost-shared program with the boiler industry to develop a low-emissions boiler system (LEBS) is in its final phases. An 80-MW proof-of-concept facility, scheduled to be on-line in 2001 at Elkhart, Illinois, will reduce SO₂ and NO_x to less than one-sixth the levels required under the New Source Performance Standards. Combined with supercritical boiler technology, the design will boost thermal efficiencies from today's 33 to 35 percent to 42 percent. More than 73 percent of the final phase's \$127 million costs will be provided by the private sector and state government.

The plant will use a low-NO_x, slagging, U-fired furnace developed under the LEBS program. A 10-MW test module for the

moving-bed copper-oxide flue-gas cleanup process will also be built and operated. Nearly all coal ash is converted by the U-fired furnace into a glass-like slag by-product that can be used in the construction industry, at a volume only one-third that of the fly ash that a conventional coal boiler would produce, significantly reducing solid-waste-handling requirements.

Cleaner, high-value solid fuels and feedstocks. DOE's coal R&D program is also expanding its research role in coal cleaning and processing. The new effort, termed the Solid Fuels and Feedstocks Program, includes research in coal and coal/biomass/waste co-processing, premium carbon products from coal, and the production of tailored feedstocks for industrial processes, chemicals, transportation fuels, and possibly even residential use.

In August 1998, DOE selected nine cost-shared projects to develop and test a broad range of innovative technologies that will produce cleaner solid fuels.

Four of the projects will develop innovative methods for recovering useable fuels from materials that otherwise would be discarded at coal cleaning plants or utility power stations, e.g., coal fines from waste ponds (2 to 3 billion tons of coal fines are in waste impoundments at coal mines and washing plants within the United States).

Another four will develop technologies that combine coal and biomass or municipal solid waste into clean-burning fuels.

The ninth will study a method for removing mercury from coal before it is burned, preventing the mercury from being released to

form a hazardous air pollutant. In addition, in-house researchers at the Federal Energy Technology Center are evaluating separation technologies for the enhanced removal of clays and pyrite from coal; the use of novel additives and heavy oil emulsions for improving the dewatering and handling of fine-size coal; novel technologies for preparing composite fuels from coal, biomass, and waste; and technologies for producing premium carbon from coal.

DOE has also supported the organization of an industry-led, cost-shared consortium, made up of the private sector and universities, to develop technologies for producing premium carbon products from coal. Research to be carried out by the consortium could include: (1) the production of feedstocks for premium carbon and graphite products, (2) improving rechargeable batteries, (3) improved coke production technologies, (4) the use of coal fuel cell applications, (5) chemically tailoring carbon molecular sieves, (6) capitalizing on adsorption qualities for water pollution control, (7) producing specialty chemicals, and (8) incorporating coal in heat-resistant applications.

As an example, technology development for premium lightweight carbon products from solid feedstocks could significantly improve transportation vehicle fuel efficiency and air quality when lightweight carbon products from coal are used to manufacture the 8 million light trucks, passenger vans, and sport-utility vehicles the United States produces each year. Coal-derived materials are expected to be more marketable (cheaper and stronger) than oil-derived plastics for reducing the weight of vehicles.

The Clean Coal Technology Program

The investment of DOE, the private sector and States in first-of-a-kind, commercial-scale clean coal technology demonstration plants – an investment that now totals \$6 billion (\$2 billion from DOE and \$4 billion from industry and States) – has provided a solid foundation for future improvements in the use of coal, including the ultimate development of the Vision 21 PowerPlex concept. Today 40 projects are part of this program – 31 of which are either operating or have completed their jointly-funded demonstration runs, one is in start-up operations, and 8 are in pre-construction stages.

For conventional power plants, technologies for NO_x reduction have been retrofitted to nearly 50 percent of the Nation's coal-fired capacity. These technologies can achieve both existing regulated emissions levels and those proposed by the Environmental Protection Agency (EPA) for 2000. The Clean Coal Technology Program has also demonstrated several advanced technologies that have significantly improved the economic and environmental performance of SO₂ controls.

For 21st century energy facilities, the Clean Coal Technology Program has pioneered the full-scale application of advanced technologies such as integrated gasification-combined cycle. Currently, three gasification-based power projects have been constructed in the program. These plants are providing valuable data that will be useful in designing the power generation train of the future Vision 21 PowerPlex.

For the liquids production aspects of future multi-product plants, the Clean Coal Technology Program has demonstrated a new,

DOE's Clean Coal Technology Project Portfolio

Category	Public/Private Investment	Projects
Advanced Electric Power Generation	\$3.2 billion	4 IGCC Systems 5 PFBC or CFBC Systems 2 Adv. Combustion/Heat Engine Systems 900 MW new capacity/800 MW repowered
Environmental Control Devices	\$700 million	7 NO _x emission control systems 5 SO ₂ emission control systems 7 combined SO _x /NO _x emission control sys. 3,170 MW total capacity
Coal Processing	\$520 million	3 producing compliance fuels for boilers 1 producing methanol 1 developing expert software
Industrial Applications	\$1.3 billion	1 to substitute coal for coke in ironmaking 1 combining direct ironmaking with power 1 reducing cement kiln emissions 1 industrial scale combustor 1 industrial scale gasifier

Figure 4 - The DOE Clean Coal Technology Program includes 40 projects with a total government/industry investment of nearly \$6 billion.

more efficient method for producing methanol from coal-derived gases using liquid slurry phase synthesis technology.

Additionally, clean coal technologies are being used to transform low-rank and noncompliance coals to useful, environmentally superior coal-based fuels for use by domestic utility and industrial coal users, and are being considered for major projects abroad. Coal-based industrial processes are gaining significant environmental and economic benefit from the demonstration of these advanced technologies.

Conclusion

As the 21st century unfolds, power and fuel producers will begin building advanced coal and power systems using technologies that have been successfully developed and demonstrated by DOE and our industry partners. These technologies will use coal and other fossil fuels with significantly higher efficiencies and with superior environmental performance than today's power plants.

DOE's coal and power research, development and demonstration program has established specific strategies for advancing the technologies of coal:

- By 2002, perform technology readiness and full-scale testing for two competing natural gas utility scale power generation concepts in the Advanced Turbine Systems program and begin adaptation to coal/biomass gas with commercial readiness by 2005;
- By 2002, remove technological limitations on hot gas filtration to achieve the full performance potential of fluidized bed combustion plant designs;
- By 2003, demonstrate proof-of-concept for a Low Emission Boiler Systems advanced pulverized coal-fired power plant;
- Extend the superior environmental performance of integrated gasification combined-cycle systems beyond electric power generation to production of market-based energy and chemical products;
- Reduce the cost of producing coal-derived transportation fuels from \$30 to \$21 per barrel;
- Enable coproduction of power, liquid fuels, and premium carbon products from coal and fuels containing biomass or solid waste;
- By 2010, establish the technological foundation for a multi-fuel, multi-product Vision 21 PowerPlex.

The technological innovations produced by this program will allow use of a *balanced* mix of fossil fuels for our electricity and transportation fuel needs.

Environmental barriers to future coal use, including smog-and acid rain-forming pollutants, will be virtually removed. Carbon dioxide emission reductions as great as 50 percent will result from thermal efficiency improvements, and potentially with affordable carbon sequestration, net carbon dioxide emissions can be reduced to zero, eliminating concerns over coal's impact on global climate change.

In short, our investment in coal technology is intended to provide the United States and other nations with the capability to use the world's full range of fossil fuel resources, promoting economic growth and prosperity while ensuring a clean, healthy environment for future generations.